Paper

AN UPDATED DOSE ASSESSMENT FOR RESETTLEMENT OPTIONS AT BIKINI ATOLL—A U.S. NUCLEAR TEST SITE

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Abstract—**On 1 March 1954, a nuclear weapon test, code-named BRAVO, conducted at Bikini Atoll in the northern Marshall Islands contaminated the major residence island. There has been a continuing effort since 1977 to refine dose assessments for resettlement options at Bikini Atoll. Here we provide a radiological dose assessment for the main residence island, Bikini, using extensive radionuclide concentration data derived from analysis of food crops, ground water, cistern water, fish and other marine species, animals, air, and soil collected at Bikini Island as part of our continuing research and monitoring program that began in 1978. The unique composition of coral soil greatly alters the relative contribution of ^{137}Cs and ^{90}Sr to the total estimated dose relative to expectations based on North American and European soils. Without counter measures, ^{137}Cs produces 96% of the estimated dose for returning residents, mostly through uptake from the soil to terrestrial food crops but also from external gamma exposure. The doses are calculated assuming a resettlement date of 1999. The estimated maximum annual effective dose for current island conditions is 4.0 mSv when imported foods, which are now an established part of the diet, are available. The 30-, 50-, and 70-y integral effective doses are 91 mSv, 130 mSv, and 150 mSv, respectively. A detailed uncertainty analysis for these dose estimates is presented in a companion paper in this issue. We have evaluated various countermeasures to reduce ^{137}Cs in food crops. Treatment with potassium reduces the uptake of ^{137}Cs into food crops, and therefore the ingestion dose, to about 5% of pretreatment levels and has essentially no negative environmental consequences. We have calculated the dose for the rehabilitation scenario where the top 40 cm of soil is removed in the housing and village area, and the rest of the island is treated with potassium fertilizer; the maximum annual effective dose is 0.41 mSv and the 30-, 50-, and 70-y integral effective doses are 9.8 mSv, 14 mSv, and 16 mSv, respectively.**

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INTRODUCTION

Bikini Atoll was one of the two sites in the Northern Marshall Islands that was used by the United States as testing grounds for the nuclear weapons program. Bikini Atoll, and the other test site Enewetak Atoll, are located in the northern part of the Marshall Islands at a latitude of about 11.5° N (Fig. 1). Twenty-three nuclear tests were conducted from 1946 to 1958 at Bikini Atoll with a total yield of 77 megatons. The BRAVO test, on 1 March 1954, had an explosive yield that greatly exceeded expectations, with the result that heavy fallout was experienced at the major residence islands of Bikini and Eneu, and lesser fallout at atolls east of Bikini Atoll. The aerial photo montage of Bikini Atoll (Fig. 2) shows the location of the BRAVO test and of Bikini and Eneu Islands. The Bikini people, since their initial relocation to Rongerik Island in 1946, have had a continuing desire to return to their homeland. In 1968, a general cleanup of debris and buildings as well as the planting of coconut, breadfruit, *Pandanus*, papaya, and banana trees began at Bikini Atoll, and a radiological survey and dose assessment were completed. Houses were then built on Bikini Island, and some Bikini families moved back to Bikini Island in 1970.

A radiological survey was conducted in 1975 when a second phase of housing was being considered, but few samples of locally grown food crops were available to confidently establish the radionuclide concentrations on Bikini Island to reliably estimate the dose; predictions based on the preliminary data indicated that when food crops matured and were available for consumption that the body burden of ^{137}Cs and resulting doses would exceed federal guidelines (Robison et al. 1977). In 1978, when the coconut trees started producing fruits, the Brookhaven National Laboratory (BNL) whole body counting confirmed that ^{137}Cs body burdens in the people on Bikini were well above the U.S. recommended level (Miltenberger and Lessard 1987). Consequently, in August 1978, Trust Territory officials arrived at Bikini Island and relocated the people to Kili Island.

Subsequently, we have developed an extensive data base for ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, and ^{241}Am concentration in the atoll ecosystem by collecting and analyzing samples of soil, vegetation, animals, ground water, cistern water and marine species in an effort to refine dose assessments for all exposure pathways for resettlement options at Bikini Atoll. Also, detailed resuspension studies have been made at Bikini, Enewetak, and Rongelap Atolls to determine the potential dose from inhalation of suspended soil containing $^{239+240}$Pu and

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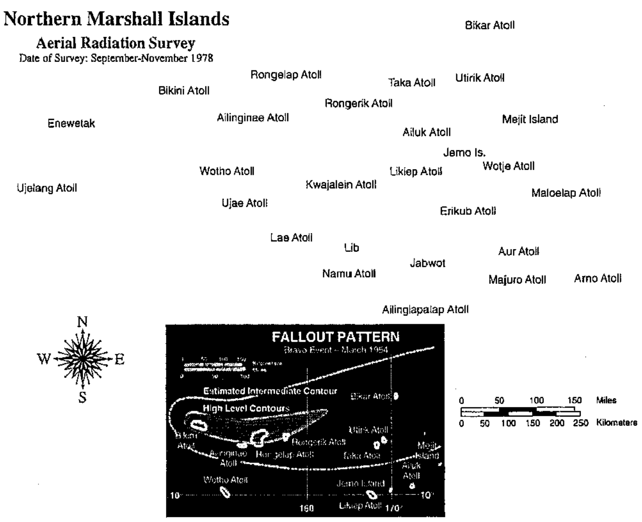

Fig. 1. A map of the Marshall Islands showing the location of the two nuclear test sites, Bikini and Enewetak Atolls.

^{241}Am. These dose assessments have been essential to define the critical radionuclides and pathways, evaluate various living patterns, and provide the communities with a basis for making informed decisions on resettlement options. A dose assessment of Bikini Island in 1982, and an earlier dose assessment of Enewetak Atoll, indicated that the most significant potential exposure pathway at the contaminated atolls was uptake of ^{137}Cs in the terrestrial food chain (Robison et al. 1980; Robison et al. 1982).

We have also conducted a research program to evaluate the effectiveness of various remedial actions designed to reduce the dose from ^{137}Cs in the food chain. The remedial measures have included excavation of the top 40 cm of the island, soil amendments (clay, zeolites), leaching (salt water irrigation), cropping (growing and harvesting sequential stands of vegetation), and chemical competition [potassium (K) addition]. Excavation of the top 40 cm of the soil column is an effective method to reduce the radionuclide concentration in the soil and subsequently the food crops, thereby reducing the dose via the food chain and external gamma. However, it does lead to a severe environmental impact on the island. Consequently, we designed our field research program to look at various remedial measures for reducing the ^{137}Cs in soil and/or blocking the uptake into food crops to give the people resettling the contaminated atolls an option to the excavation of the top soil on their islands. The most effective method of all the tested methods, and by far the easiest to implement, is the addition of K to the soil. Not only does the K treatment reduce the intake of ^{137}Cs from the direct ingestion of the food crops, but it also reduces the ^{137}Cs intake from coconut crabs, pigs, and chickens that feed on the vegetation.

In this report we present the most recent dose estimates before and after the K countermeasure designed to reduce the dose to people resettling Bikini Island.

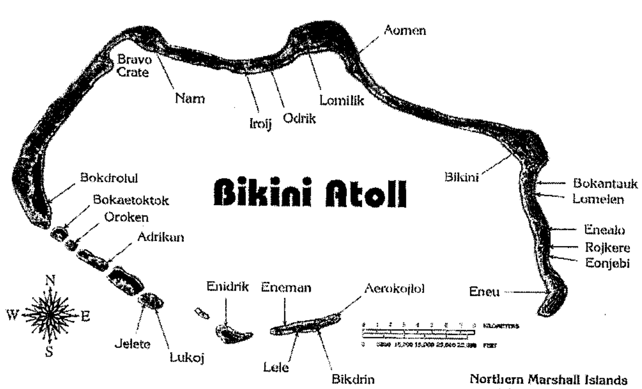

Fig. 2. A photographic montage of Bikini Atoll showing the location of the various islands.

EXPOSURE PATHWAYS

The radiological dose to inhabitants at the atoll occurs from both external and internal exposure. Each of these two categories can be broken down further into the following exposure pathways: (1) External exposure: natural background radiation; nuclear test-related radiation, (2) Internal exposure: natural background radiation; nuclear test-related radiation—radionuclides in terrestrial foods, marine foods, drinking water and radionuclides inhaled.

The external natural background radiation in the Northern Marshall Island Atolls is 9.0×10^{-10} C kg^{-1} (3.5 μR h^{-1}) or 0.22 mSv y^{-1} (Gudiksen et al. 1976) due to cosmic radiation; the external background dose due to terrestrial radiation is very low in the Marshall Islands because of the composition of the soil. The internal effective dose is about 2.2 mSv y^{-1} for natural occurring radionuclides such as ^{40}K, ^{210}Po, and ^{210}Pb that result from consumption of local and imported foods (Noshkin et al. 1994; Robison et al. 1997). The natural background dose is not included in the doses presented in the paper unless specifically stated.

DATA BASES

External exposure measurements

The external exposure rates at Bikini Atoll were measured by Edgerton Germeshausen and Grier (EG&G) as part of the aerial survey conducted in the 1978 Northern Marshall Islands Radiological Survey (NMIRS) (Tipton and Meibaum 1981). The average exposure rate on Bikini Island as measured by EG&G in 1978 was about 8×10^{-9} C kg^{-1} (31 μR h^{-1}). In 1986 and 1988, additional external gamma measurements were made by LLNL of ^{137}Cs and ^{60}Co inside and outside houses and other buildings, and around the village area; crushed coral placed around the buildings provides shielding in addition to the buildings. Measurements at Bikini Island indicate that the average exposure inside the houses is about 5.4×10^{-10} C kg^{-1} (2.1 μR h^{-1}) while in the immediate area around the houses it is 2.8×10^{-9} C kg^{-1} (11 μR h^{-1}).

External beta-particle exposure

The unshielded beta contribution to the external dose was estimated at Enewetak Atoll in 1980 (Crase et al. 1982). Studies at Bikini Atoll using new, thinner thermoluminescent dosimeters (TLDs) indicate that the dose over open ground at 1 cm height is about three times that of 1 m height (Shingleton et al. 1987). Thus, the unshielded beta dose at 1 cm on Bikini Island could be equal to or slightly greater than the external gamma dose. However, for a significant part of the day the eyes, upper body, and gonads are at 0.8 m or more in height above the ground surface. The walls and floors of the houses and the crushed coral customarily put around houses and the village area absorb most of the beta radiation. In addition, any clothing, shoes, zories, *Pandanus* mats, or other coverings also greatly reduce exposure to beta radiation.

Airborne radionuclide concentrations

Airborne concentrations of $^{239+240}$Pu and ^{241}Am are estimated from data derived from resuspension experiments conducted at Enewetak Atoll in 1977, Bikini Atoll in 1978, and Rongelap Atoll in 1991. We briefly describe the resuspension methodology here; more detail can be found in Shinn et al. (1997). Four simultaneous experiments were conducted: (1) a characterization of the normal (background) suspended aerosols and the contributions of sea spray off the windward beach leeward across the island; (2) a study of resuspension of radionuclides from a field purposely laid bare by bulldozers as a worst-case condition; (3) a study of resuspension of radioactive particles by vehicular and foot traffic; and (4) a study of personal inhalation exposure using small air samplers carried by volunteers during daily routines. The "normal" or "background" mass loading (the mass of solid material per unit volume of air) measured by gravimetric methods for the atolls is approximately 55 μg m^{-3}. The data from the Bikini experiments indicate that 34 μg m^{-3} of this total is due to sea salt that is present across the entire island as a result of ocean, reef, and wind actions. The mass loading due to terrestrial origins is, therefore, about 21 μg m^{-3}. The highest terrestrial mass loading observed was 136 μg m^{-3} immediately after bulldozing.

Concentrations of $^{239+240}$Pu were determined for collected aerosols (1) for normal ground cover and conditions in coconut groves, (2) for high-activity conditions, i.e., areas being cleared by bulldozers and being tilled, and (3) for stabilized bare soil, i.e., cleared areas after a few days' weathering. The plutonium concentration in the collected aerosols changes with respect to the plutonium concentration in surface soil for each of these situations. We have defined an enhancement factor (EF) as the $^{239+240}$Pu concentration in the collected soil-aerosol mass divided by the $^{239+240}$Pu surface-soil (0- to 5 cm) concentration. The EF of less than 1 (EF <1) for the normal, open-air conditions is apparently the result of selective particle resuspension in which the resuspended particles have a different plutonium concentration than is observed in the total 0- to 5-cm soil sample. Similarly, the enhancement factor of 3 for high-resuspension conditions results from the increased resuspension of particle sizes with a higher plutonium concentration than observed in the total 0- to 5-cm soil sample.

We have developed additional personal-enhancement factors (PEF) from personal air-sampler data. These data represent the enhancement that occurs around individuals due to their daily activities. The total enhancement factor used to estimate the amount of suspended plutonium is the EF (0.82 for normal resuspension and 3.1 for high resuspension) multiplied by the PEF (1.9 for normal resuspension and 0.92 for high resuspension). Consequently, the total enhancement used for normal resuspension conditions is 1.5 and for high-resuspension conditions is 2.9.

To calculate inhalation exposure, we assume that a person spends 1 h d^{-1} in high-resuspension conditions, 23 h d^{-1} under normal resuspension conditions, and has a breathing rate of 22 m^3 d^{-1} (1.2 m^3 under high-resuspension conditions and 20.9 m^3 under normal-resuspension conditions). An analysis of breathing rates based on energy expenditure indicates that the volume of air breathed in a 24 h period may be significantly less than the 22 m^3 d^{-1} recommended by ICRP (Layton, 1993). The radionuclide concentrations in surface soil (0- to 5-cm) for Bikini Island complete the information necessary for calculation of plutonium and americium intake through inhalation.

Radionuclides in marine foods, soil, and terrestrial food

The average concentrations of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, and ^{241}Am in marine foods and terrestrial foods are listed in Table 1. Most of the data for the marine foods is a result of work conducted by Noshkin et al. (1988). The data for the terrestrial foods are part of our continuing program where samples have been collected and analyzed from 1975 through 1993 on Bikini Island. The number of samples analyzed are as follows: 812 drinking coconut meat, 747 drinking coconut juice, 188 copra meat, 177 copra juice, 69 *Pandanus*, 41 breadfruit, 93 papaya, 53 squash, 39 banana and 36 animals. The median concentration of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am in soil profiles are listed in Table 2. The soil data are also part of our continuing program.

Radionuclides in drinking water

The major source of water used in cooking and for drinking is rainwater collected from roofs of houses and other buildings that is stored in cisterns. If extreme drought conditions occur, then the freshest groundwater available is used; the groundwater is contaminated with radionuclides from the soil column. The concentrations of radionuclides in both cistern water and groundwater are listed in Table 1. For the dose estimates, we use an

Table 1. Diet model for adults greater than 18 y living on Bikini Island for current conditions and for the soil removal and potassium treatment option.

	Imported foods diet		Local foods only diet			Specific activity in 1999 (Bq g^{-1} wet wt.)				
						Current conditions	Scrape + K option	Common to both current and scrape + K option		
Local Food	g d^{-1}	Kcal d^{-1}	g d^{-1}	Kcal d^{-1}	Kcal g^{-1}	^{137}Cs	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
Reef fish	24.2	33.8	86.8	121	1.40	2.9×10^{-3}	2.9×10^{-3}	4.5×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Tuna	13.9	19.4	72.0	101	1.40	4.5×10^{-3}	4.5×10^{-3}	5.3×10^{-6}	1.9×10^{-6}	1.3×10^{-6}
Mahi Mahi	3.56	3.92	21.4	23.5	1.10	4.5×10^{-3}	4.5×10^{-3}	5.3×10^{-6}	1.9×10^{-6}	1.3×10^{-6}
Marine Crabs	1.68	1.51	19.5	17.6	0.90	1.4×10^{-3}	1.4×10^{-3}	8.9×10^{-5}	3.6×10^{-5}	2.6×10^{-5}
Lobster	3.88	3.49	35.2	31.7	0.90	1.4×10^{-3}	1.4×10^{-3}	8.9×10^{-5}	3.6×10^{-5}	2.6×10^{-5}
Clams	4.56	3.65	58.1	46.5	0.80	4.6×10^{-4}	4.6×10^{-4}	8.7×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Trochus	0.10	0.080	0.24	0.19	0.80	4.6×10^{-4}	4.6×10^{-4}	8.7×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Tridacna Muscle	1.67	2.14	11.4	14.6	1.28	4.6×10^{-4}	4.6×10^{-4}	8.7×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Jedrul	3.08	2.46	19.4	17.4	0.80	4.6×10^{-4}	4.6×10^{-4}	8.7×10^{-5}	8.3×10^{-4}	4.6×10^{-4}
Coconut Crabs	3.13	2.19	24.9	17.5	0.70	3.7×10^{-1}	3.7×10^{-1}	5.2×10^{-2}	3.8×10^{-5}	2.8×10^{-5}
Land Crabs	0.00	0.00	0.00	0.00	0.70	3.7×10^{-1}	3.7×10^{-1}	5.2×10^{-2}	3.8×10^{-5}	2.8×10^{-5}
Octopus	4.51	4.51	49.0	49.0	1.00	1.8×10^{-3}	1.8×10^{-3}	4.5×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Turtle	4.34	3.86	17.8	15.8	0.89	2.8×10^{-4}	2.8×10^{-4}	4.5×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Chicken Muscle	8.36	14.2	31.2	53.0	1.70	1.5×10^{-1}	2.1×10^{-2}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Chicken Liver	4.50	7.38	17.7	29.0	1.64	1.5×10^{-1}	2.1×10^{-2}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Chicken Gizzard	1.66	2.46	3.32	4.91	1.48	1.5×10^{-1}	2.1×10^{-2}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Pork Muscle	5.67	25.5	13.9	62.6	4.50	7.0×10^{0}	1.6×10^{0}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Pork Kidney	NR	0.00	NR	0.00	1.40	6.5×10^{0}	1.4×10^{0}	6.2×10^{-3}	3.5×10^{-5}	1.2×10^{-5}
Pork Liver	2.60	6.27	6.70	16.1	2.41	3.6×10^{0}	8.1×10^{-1}	2.9×10^{-3}	1.2×10^{-4}	5.2×10^{-5}
Pork Heart	0.31	0.60	0.62	1.21	1.95	4.2×10^{0}	9.8×10^{-1}	1.5×10^{-3}	5.9×10^{-6}	1.8×10^{-5}
Bird Muscle	2.71	4.61	26.4	44.8	1.70	2.5×10^{-3}	2.5×10^{-3}	2.3×10^{-4}	1.3×10^{-5}	6.5×10^{-6}
Bird Eggs	1.54	2.31	22.8	34.1	1.50	6.7×10^{-4}	6.7×10^{-4}	3.6×10^{-4}	1.3×10^{-5}	6.5×10^{-6}
Chicken Eggs	7.25	11.8	41.2	67.2	1.63	1.5×10^{-1}	2.1×10^{-2}	1.5×10^{-3}	7.7×10^{-6}	6.0×10^{-6}
Turtle Eggs	9.36	14.0	235	352	1.50	2.8×10^{-4}	2.8×10^{-4}	4.5×10^{-5}	1.3×10^{-5}	6.5×10^{-6}
Pandanus Fruit	8.66	5.20	63.0	37.8	0.60	3.9×10^{0}	1.9×10^{-1}	1.2×10^{-1}	3.2×10^{-6}	3.8×10^{-6}
Pandanus Nuts	0.50	1.33	2.00	5.32	2.66	3.9×10^{0}	1.9×10^{-1}	1.2×10^{-1}	3.2×10^{-6}	3.8×10^{-6}
Breadfruit	27.2	35.3	186	242	1.30	3.8×10^{-1}	1.9×10^{-2}	6.9×10^{-2}	1.8×10^{-6}	1.2×10^{-6}
Coconut Juice	99.1	10.9	333	36.6	0.11	1.2×10^{0}	5.8×10^{-2}	4.5×10^{-4}	1.0×10^{-6}	8.5×10^{-6}
Coconut Milk	51.9	179	122	421	3.46	5.4×10^{0}	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Tuba/Jekero	0.00	0.00	0.00	0.00	0.50	5.4×10^{0}	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Drinking Coco Meat	31.7	32.3	181	184	1.02	2.9×10^{0}	1.5×10^{-1}	5.9×10^{-3}	2.7×10^{-6}	3.6×10^{-6}
Copra Meat	12.2	50.3	71.3	295	4.14	5.4×10^{0}	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Sprout. Coco	7.79	6.23	122	97.8	0.80	5.4×10^{0}	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Marsh. Cake	11.7	39.2	0.00	0.00	3.36	5.4×10^{0}	2.7×10^{-1}	3.2×10^{-3}	1.9×10^{-6}	1.1×10^{-6}
Papaya	6.59	2.57	27.0	10.5	0.39	2.2×10^{0}	1.1×10^{-1}	4.9×10^{-2}	2.5×10^{-6}	3.6×10^{-7}
Squash	NR	0.00	NR	0.00	0.47	1.2×10^{0}	5.9×10^{-2}	6.8×10^{-2}	2.2×10^{-5}	3.0×10^{-6}
Pumpkin	1.24	0.37	5.44	1.63	0.30	1.2×10^{0}	5.9×10^{-2}	6.8×10^{-2}	2.2×10^{-5}	3.0×10^{-6}
Banana	0.020	0.018	0.58	0.51	0.88	1.8×10^{-1}	8.9×10^{-3}	4.9×10^{-2}	2.5×10^{-6}	3.6×10^{-7}
Arrowroot	3.93	13.6	94.9	328	3.46	5.4×10^{-2}	5.4×10^{-2}	6.8×10^{-2}	2.2×10^{-5}	3.0×10^{-6}
Citrus	0.10	0.049	0.20	0.10	0.49	1.2×10^{-1}	6.0×10^{-3}	4.9×10^{-2}	2.5×10^{-6}	3.6×10^{-7}
Rainwater	313	0.00	629	0.00	0.00	4.3×10^{-5}	4.3×10^{-5}	1.4×10^{-5}	3.3×10^{-7}	3.7×10^{-8}
Wellwater	207	0.00	430	0.00	0.00	4.5×10^{-3}	4.5×10^{-3}	1.2×10^{-3}	6.1×10^{-7}	4.4×10^{-7}
Malolo	199	0.00	0.00	0.00	0.00	4.3×10^{-5}	4.3×10^{-5}	1.4×10^{-5}	3.3×10^{-7}	3.7×10^{-8}
Coffee/Tea	228	0.00	0.00	0.00	0.00	4.3×10^{-5}	4.3×10^{-5}	1.4×10^{-5}	3.3×10^{-7}	3.7×10^{-8}
Soil[a]	0.10	0.00	0.10	0.00	0.00	1.3×10^{0}		9.9×10^{-1}	2.0×10^{-1}	1.2×10^{-1}
Soil[b]	0.10	0.00	0.10	0.00	0.00		3.9×10^{-1}	7.3×10^{-1}	5.5×10^{-2}	4.7×10^{-2}
Total Local	1,322	547	3,083	2,783						

[a] Soil represents the current conditions on Bikini Island, Bq g^{-1} dry wt.
[b] Soil represents the soil removal and potassium treatment option for Bikini Island, Bq g^{-1} dry wt.

intake of 1 L d^{-1} of drinking water. We assume for the dose assessment that cistern water is available for 60% of the year and that groundwater is used for 40% of the year. The rainfall during the dry part of the year (December through April) can sometimes be very low, such that fresh water supplies are exhausted and the people resort to the use of brackish but potable ground water. The 40% intake of groundwater over a lifetime is very conservative in that this process does not occur every year, and some years for only a month or two. Soda and fruit drinks are frequently available and account for some of the daily fluid intake. The total daily drinking fluid intake from all these sources is between 2 and 2.5 L d^{-1}.

Diet

The radiological dose from the ingestion pathway will scale directly with the total intake of radionuclides, which is proportional to the quantity of locally grown

Table 2. Median (and mean) concentrations in Bq g^{-1} dry weight of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu, and ^{241}Am in soil at Bikini Island.

Soil depth, cm	No. of samples	^{137}Cs	No. of samples	^{90}Sr	No. of samples	$^{239+240}$Pu	No. of samples	^{241}Am
Interior of island								
0–5	254	2.3 (3.0)	55	1.7 (2.1)	54	0.32 (0.42)	157	0.26 (0.30)
5–10	254	1.2 (1.8)	55	2.0 (2.4)	55	0.29 (0.44)	151	0.19 (0.27)
10–15	253	0.58 (1.0)	55	1.5 (2.3)	55	0.15 (0.34)	127	0.081 (0.18)
15–25	248	0.19 (0.48)	54	0.73 (1.4)	51	0.053 (0.16)	80	0.026 (0.11)
25–40	246	0.071 (0.19)	47	0.47 (0.77)	46	0.0081 (0.061)	59	0.012 (0.051)
40–60	217	0.018 (0.019)	13	0.32 (0.65)	13	0.011 (0.035)	23	0.017 (0.073)
0–40	240	0.70 (0.91)	47	1.1 (1.5)	45	0.17 (0.21)	53	0.11 (0.14)
Village area								
0–5	74	1.2 (2.0)	44	1.0 (2.0)	43	0.20 (0.40)	63	0.11 (0.22)
5–10	73	1.0 (1.6)	44	1.2 (2.0)	43	0.30 (0.40)	62	0.13 (0.20)
10–15	72	0.81 (1.2)	44	1.5 (1.7)	43	0.22 (0.28)	63	0.12 (0.19)
15–25	71	0.53 (1.0)	44	0.90 (1.6)	41	0.14 (0.25)	59	0.064 (0.15)
25–40	71	0.18 (0.80)	43	0.62 (1.7)	42	0.064 (0.25)	52	0.059 (0.13)
40–40	46	0.028 (0.23)	18	0.32 (1.2)	17	0.0058 (0.11)	20	0.012 (0.11)
0–40	71	0.67 (1.1)	43	1.6 (1.5)	41	0.24 (0.29)	51	0.13 (0.17)

Note: Decay corrected to 1999. Number in parentheses is the arithmetic mean.

foods that are consumed. Therefore, a reasonable estimate of the average daily consumption rate of each food item is essential. Our laboratory, and others, in concert with local government authorities, with the legal representatives of the people, and with Peace Corps representatives, and anthropologists have endeavored to establish and document pertinent trends, cultural influences and economic realities. The diet model we use for estimating the intake of local plus imported foods (IA diet model) is presented in Table 1. The basis of this diet model was the survey of the Ujelang community in 1978 by the Micronesian Legal Services Corporation (MLSC) staff and the Marshallese school teacher on Ujelang (Robison et al. 1983). A diet based on consumption of only local foods, i.e., imported foods unavailable (IUA), is also listed in Table 1.

The ^{137}Cs concentration in most dietary items is based on direct measurement. There are a few special cases for animals or fowl that may roam the island. Treatment is assumed to affect ingested ^{137}Cs in pork to the extent that pigs eat treatment-affected vegetation and soil from areas where soil has or has not been removed. Food intakes for penned pigs are assumed to be 90% vegetation and 10% village area soil, while those for unpenned pigs are assumed to be 90% vegetation and 10% soil from areas outside the village. The pork from penned and unpenned pigs are each assumed to comprise 50% of total pork consumed. Chicken is assumed to correspond to the scenario assumed for unpenned pigs. Coconut crabs are assumed to be taken from the western islands of Bikini Atoll where they are plentiful.

DOSE METHODOLOGY

External exposure

Gamma radiation—Current conditions. The external exposure calculations for gamma radiation are based on measurements made on Bikini Island in 1978 and 1988 that are decay corrected to 1999. The following arbitrary distribution of time was used to develop the average external exposure:

- Ten h d^{-1} are spent in the house where the exposure rate is 4.1×10^{-10} C kg^{-1} (1.6 μR h^{-1});
- Nine h d^{-1} around the house and village area where the exposure rate is assumed to be 2.2×10^{-9} C kg^{-1} (8.5 μR h^{-1}) (weighted average of outside house and general village sites);
- Three h d^{-1} in the interior region of the island where the average exposure is 4.9×10^{-9} C kg^{-1} (19 μR h^{-1}) (Tipton and Meibaum 1981);
- Two h d^{-1} on the beach or lagoon where the exposure is 2.58×10^{-11} C kg^{-1} (0.1 μR h^{-1}), based on EG&G data (Tipton and Meibaum 1981).

Although the selection of this particular time distribution is arbitrary, general discussions with Marshallese people and observations while we have been in the islands make the selection reasonable. The resultant contributions of ^{137}Cs to the average dose equivalent from a year's occupancy of various island areas described in the above scenario are as follows: inside houses, 0.045 mSv; elsewhere in the housing and village area, 0.21 mSv; island interior, 0.16 mSv; beaches and lagoon, 0.55 μSv. The total average external dose attributable to such occupancy in 1999 on Bikini Island is about 0.42 mSv y^{-1}. Natural external background is about 0.22 mSv y^{-1}.

Gamma radiation—Soil removal in the housing and village area. The interior portion of the island is assumed to remain the same, i.e., 4.9×10^{-9} C kg^{-1} (19

μR h^{-1}), as listed under the current conditions. The time distributions are also the same.

The exposure rate in the village area and inside the houses after soil removal and placement of crushed coral on the ground surface is assumed to be 5.2×10^{-11} C kg^{-1} (0.2 μR h^{-1}) and 2.58×10^{-11} C kg^{-1} (0.1 μR h^{-1}), respectively.

The resultant contributions of ^{137}Cs to the average dose equivalent from a year's occupancy of various island areas described in the above scenario are as follows: inside houses, 0.0028 mSv; elsewhere in the housing and village area, 0.0050 mSv; island interior, 0.16 mSv; beaches and lagoon, 0.55 μSv. The total average external effective dose attributable to such occupancy in 1999 on Bikini Island is about 0.17 mSv y^{-1}. Natural external background is about 0.22 mSv y^{-1}.

Beta radiation. It is impossible to predict precisely what the beta dose to the skin will be, but it is clear that the "shallow dose" due to both beta particles and external gamma exposure will be only slightly greater than the dose estimated for external gamma whole-body exposure. This higher "shallow dose" will occur primarily to the most exposed parts of the body, usually the arms, lower legs, and feet. The skin is a much less sensitive organ to radiation than other parts of the body; consequently, the beta contribution to the total effective dose is extremely small.

Internal exposure

^{137}Cs. The conversion from the intake of ^{137}Cs to the dose equivalent for the adult is based upon the ICRP methods described in ICRP Publications 56, 61 (ICRP 1990, 1991), which are based on Leggett's model (Leggett 1986). The biological half-life of ^{137}Cs is determined as a function of mass (i.e., age) by the methods described in the Leggett (1986). In a separate report we estimated the comparative doses between adults and children (Robison and Phillips 1989). The results indicate that the estimated integral effective dose for adults due to ingestion of ^{137}Cs and ^{90}Sr can be used as a conservative estimate for intake beginning at any other age. In this report we calculate only the doses to adults.

^{90}Sr. The model developed by Leggett et al. (1982) is based on the structure and function of bone compartments as generally outlined in the ICRP model (ICRP 1990). The bone is assumed to be composed of a structural component associated with bone volume, which includes the compact cortical bone, a large portion of the cancellous (trabecular) bone, and a metabolic component associated with bone surfaces. We will not discuss further details of these models, but refer the reader to the original articles and their associated references for additional discussion and clarification (Leggett et al. 1982; Cristy et al. 1984). Doses listed in this paper are calculated from the Leggett model

Transuranic radionuclides ($^{239+240}$Pu and ^{241}Am)

Ingestion. We calculated the dose equivalent from ingestion of transuranic radionuclides ($^{239+240}$Pu and ^{241}Am) by ICRP methods (ICRP 1986, 1993a). The amount of ingested plutonium or americium crossing the gut wall to the blood is assumed to be 5×10^{-4} for plutonium and americium in vegetation, and 10^{-5} (Harrison et al. 1989) and 5×10^{-4} for the fraction of plutonium and americium, respectively, ingested via soil. Of the fraction of plutonium or americium reaching the blood, 45% is assumed to go to bone and 45% to the liver (ICRP 1986, 1993a). The biological half-life is 50 y in bone and 20 y in liver for both elements (ICRP 1986, 1993a). The quality factor is 20 for the alpha particles.

Inhalation. The dose equivalent from inhalation for the transuranic radionuclides is based on the intake determined from the assumptions discussed in the section on a airborne, respirable radionuclide concentrations of this paper and the ICRP new lung model dose methodology (ICRP 1986, 1990, 1994). The $^{239+240}$Pu and ^{241}Am are considered class W particles, and the quality factor is 20 for the alpha particles. Other parameters are as described in the ICRP method previously discussed for the ingestion of transuranic radionuclides. The activity-median aerodynamic diameter (AMAD) is assumed to be 1 μm, which provides a slightly conservative dose estimate (i.e., slightly higher dose) because the observed AMAD was about 2.5 μm in the Bikini experiment (Shinn et al. 1997).

^{210}Po, ^{210}Pb. The estimated dose from ingestion of natural ^{210}Po and ^{210}Pb is based on ICRP data and methods (ICRP 1991). The weighted committed dose equivalent per unit intake of activity for ^{210}Po is 2.2×10^{-7} Sv Bq^{-1}, and for ^{210}Pb it is 1×10^{-6} Sv Bq^{-1}.

Body weights and biological half-life of ^{137}Cs

Data from Brookhaven National Laboratory (BNL) have been summarized to determine the body weights of the Marshallese people (Conard et al. 1959, 1960, 1963, 1975; Miltenberger et al. 1980a‡, 1980b). The average adult male body weight is 72 kg for Bikini, 71 kg for Enewetak, and 69 kg for Utirik. We have used 70 kg as the average male body weight in our dose calculations. The average biological half-life for the long-term compartment for ^{137}Cs in adults is listed as 110 d in ICRP (1990) and NCRP (1977). This is consistent with data obtained by BNL on the half-time of the long-term compartment in Marshallese (Miltenberger et al. 1981; Miltenberger and Lessard 1987). The distribution of biological half-life in 23 Marshallese adult males is lognormal with a median of 115 d, a mean of 119 d, and a range of 76–178 d. We used the 110 d half-life because

‡ Personal communication, Miltenberger, R. P.; Greenhouse, N.; Cua, F.; Lessard, E. Working Draft: Dietary radioactivity intake from bioassay data a model applied to cesium-137 intake by Bikini Island residents. Brookhaven National Laboratory; 1980.

it is based on a much larger sample population and the difference between it and the 115 d half-life observed in 23 Marshallese males is minimal.

COUNTERMEASURES—MITIGATION OF FOOD-CHAIN DOSE

All remedial actions were evaluated against the criteria of reducing the estimated average maximum annual effective dose to about the world-wide average background effective dose of 2.4 mSv. A countermeasure is not recommended to the communities for consideration if it cannot lead to a dose below this criterion. Countermeasures evaluated to reduce the dose from ^{137}Cs through the terrestrial food chain include salt water irrigation (leaching), zeolites and mineral clay soil amendments, repeated cropping, soil removal (excavation), and potassium (K) treatment. All but the last two options have been discarded as either less effective or difficult to implement or both.

Experiments at Eneu Island at Bikini Atoll using potassium-rich fertilizers (16N-16P-16K) or KCl show a reduction of about 20-fold in the concentration of ^{137}Cs in coconut meat and fluid; the ^{137}Cs concentrations in foods grown without potassium-rich fertilizer range from 0.24 to 1.3 Bq g^{-1} wet weight, while the ^{137}Cs concentrations in foods grown using potassium-rich fertilizer are less than 0.074 Bq g^{-1} (Robison and Stone 1992). We began a similar experiment on Bikini Island where the ^{137}Cs concentrations in soil, coconut, breadfruit, and other local foods are about 8 to 10 times higher than at Eneu Island. The results of that experiment through May 1994 show that we have reduced the ^{137}Cs concentration in coconut meat and fluid from a range of 5.6 to 11 Bq g^{-1} wet weight to about 0.55 to 0.74 Bq g^{-1} wet weight; in those trees where the initial concentration was between 1.9 to 3.7 Bq g^{-1} wet weight, the potassium treatment has reduced the ^{137}Cs concentration to less than 0.35 Bq g^{-1} (Robison and Stone 1992). A second treatment 51 mo after the original K application showed a further reduction in the ^{137}Cs concentration in drinking coconut meat (Fig. 3). Moreover, one row of coconuts (K1000 1 treatment) that has received no K since the original treatment shows only a slight increase in ^{137}Cs concentration after about 6 y. Several other experiments with coconuts support the above results (Robison and Stone 1992). The same reduction in the uptake of ^{137}Cs has also been observed in breadfruit, *Pandanus* fruit, papaya, and several grain and vegetable crops.

Of course, excavation of the top 30 to 40 cm of soil over the whole island also will effectively reduce the potential dose, both external and internal. This option, however, would entail significant environmental cost, as well as high dollar cost. The removal of the top 30 to 40 cm of soil would carry with it the removal of essentially all of the organic material—material that has taken centuries to develop and that contains most all of the nutrients needed for plant growth and provides water-retention capacity of the coral soil. Moreover, this would obviously require removing all the mature coconut, breadfruit, *Pandanus*, lime, and other trees that supply food, windbreak, and shade at the island and take years to mature. This option would thus necessitate a very long-term commitment to rebuild the soil and revegetate the island. Such a commitment would, in turn, seem to suggest a continuous infusion of effort and expertise, the availability of which does not now seem assured. We have not addressed the matter of the disposal of the very large quantity of removed soil and vegetation, but recent experiences at other locations indicate that this would present a formidable problem of both acceptance and cost.

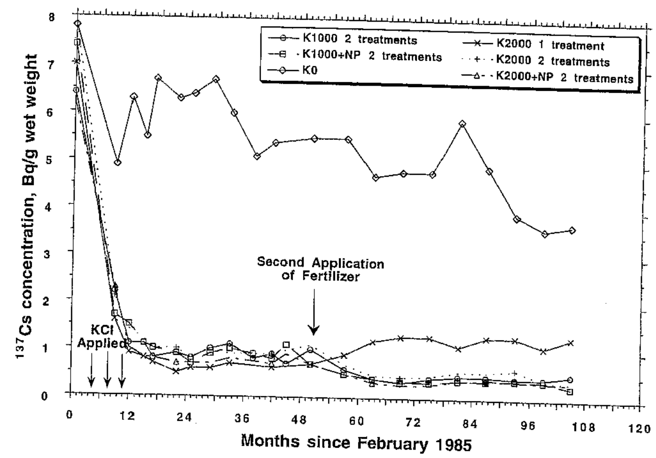

Fig. 3. The reduction in the uptake of ^{137}Cs into drinking coconuts at Bikini Island after an initial and a second application of potassium.

UNCERTAINTY AND INTERINDIVIDUAL VARIABILITY IN ESTIMATED BIKINI DOSES

Doses estimated as described in the Dose Methodology section are based on distributed quantities reflecting either *uncertainty* (i.e., lack of knowledge concerning "the true" value) or *interindividual variability* (which hereafter will be referred to simply as "variability," i.e., heterogeneity in values pertaining to different people), or both; consequently, predicted dose will necessarily reflect both of these characteristics as well. To characterize such uncertainty and variability it is necessary to systematically distinguish these attributes as each or both may pertain to each input variate (Bogen and Spear 1987; IAEA 1996; Bogen 1991; NRC 1993). Another paper in this issue (Bogen et al. 1997) provides a detailed analysis of the methodology and results of the uncertainty and interindividual variability in the estimated doses at Bikini Islands.

RESULTS

The estimated maximum annual and integral effective dose for people resettling Bikini Island are calculated using our diet model, the average radionuclide concentrations in foods, the average biological removal rates and depositions for the radionuclides in organs or the whole body, and the average external dose rates. Doses are presented for two cases: imported foods available (IA), and imported foods unavailable (IUA); that is, consumption of only local foods. The IA diet consists of about 60% imported foods and 40% locally grown foods. The doses listed under the case "IUA" are calculated assuming no imported foods are available and that only local foods are consumed over the entire lifetime of the people's residence on Bikini Island. Our observations lead us to conclude that the latter case is unrealistic over any extended period of time and highly conservative. Nonetheless, even though such a diet will never again exist in the Marshall Islands, the dose based on such a diet are presented here so that the reader may apply different assumptions, or the results of future observations, and develop an apportioned dose estimate.

The doses are also calculated for both the current island conditions (i.e., no remediation) and for the cleanup scenario, where the top 40 cm of soil is removed from the housing and village area where people spend most of their time, and the rest of the island (coconut grove) is treated with potassium fertilizer.

As part of a recent National Academy of Sciences review of our program it was recommended that we double the calorie intake of the diet consisting of only local foods (IUA) from the survey because the diet as developed from the survey data would lead to weight loss and could not be sustained for long periods of time. We did this by doubling the intake of all foods for the original IUA diet. The doses listed in the following tables for the IUA diet are, consequently, based on twice the radionuclide daily intakes.

Estimated doses for resettlement for current conditions on Bikini Island

The average maximum annual effective dose estimated for residents on Bikini Island when imported foods are available (Table 3) is 4.0 mSv. The 30-, 50- and 70-y integral effective dose for residents of Bikini Island, for IA, and local foods only (IUA) diets are listed in Table 4. The doses are presented by internal and external exposure pathways and by radionuclide so that the contribution of each pathway and nuclide can be evaluated. The 30-, 50- and 70-y integral effective doses are 91 mSv, 130 mSv, and 150 mSv, respectively; the same doses for the local foods only diet (IUA) are 350 mSv, 480 mSv, and 560 mSv.

The relative contribution of each of the exposure pathways is presented in Table 5. The dose from the terrestrial food-chain pathway accounts for about 90% of the total estimated 30-y integral effective dose; ^{137}Cs accounts for about 96% of this dose, and ^{90}Sr for about 1%. Any procedure that would either block the uptake of ^{137}Cs into food crops and/or eliminate it from the soil column would substantially reduce the potential exposure of the people living on Bikini Island. The external gamma exposure is next in significance and contributes about 10% of the 30-y integral effective dose.

Estimated doses for resettlement after soil removal in the housing and village area and potassium treatment of the rest of the island

The average maximum annual effective dose for this scenario is estimated to be 0.41 mSv for the IA diet, and 1.2 mSv for the IUA diet (Table 6). The 30-, 50-, and 70-y integral doses for the IA diet are 9.8 mSv, 14 mSv, and 16 mSv; and for the IUA diet they are 31 mSv, 43 mSv, and 50 mSv, respectively (Table 7). For both diet models the counter measure scenario leads to about a 10-fold reduction in the dose. The relative contribution for each pathway for this countermeasure scenario is listed in Table 8.

A summary of the doses for the two island conditions and two diet scenarios showing the dose reductions

Table 3. The maximum annual organ dose equivalent and effective dose rate in mSv y^{-1} for Bikini Island residents for current island conditions when imported foods are available.

		Dose equivalent rate, mSv y^{-1}			
	Weight factor	External gamma	Internal ingestion	Internal inhalation	Total organ
Bone marrow	0.12	0.40	4.0	0.0021	4.4
Bone surface	0.01	0.40	4.2	0.024	4.6
Gonads	0.20	0.40	3.7	0.00031	4.1
Lung	0.12	0.40	3.4	0.0033	3.7
Breast	0.05	0.40	3.0	0.000063	3.4
Thyroid	0.05	0.40	3.4	0.000063	3.8
Liver	0.05	0.40	3.6	0.0049	4.0
Colon	0.12	0.40	3.7	0.000068	4.1
Stomach	0.12	0.40	3.6	0.000063	3.9
Bladder	0.05	0.40	3.7	0.000063	4.1
Oesophagus	0.05	0.40	3.5	0.000063	3.8
Skin	0.01	0.40	2.9	0.000063	3.2
Remainder	0.05	0.40	3.7	0.000063	4.1
Total effective dose equivalent rate[a]					4.0

[a] Weighting factor multiplied by total organ dose.

Table 4. The 30-, 50- and 70-y integral effective dose for Bikini Island residents for current island conditions when imported foods are available and when only local foods are consumed. Numbers in parentheses are the doses for the "local food only" diet (IUA).

	Integral effective dose, mSv					
	30 y	30 y	50 y	50 y	70 y	70 y
External	9.1	(9.1)	13	(13)	15	(15)
Internal						
Ingestion						
^{137}Cs	81	(330)	110	(460)	130	(530)
^{90}Sr	0.85	(5.9)	1.2	(8.6)	1.5	(10)
$^{239+240}Pu$	0.011	(0.098)	0.028	(0.24)	0.051	(0.44)
^{241}Am	0.018	(0.062)	0.043	(0.15)	0.075	(0.26)
Inhalation						
$^{239+240}Pu$	0.069	(0.069)	0.16	(0.16)	0.23	(0.23)
^{241}Am	0.050	(0.050)	0.11	(0.11)	0.15	(0.15)
Total[a]	91	(350)	130	(480)	150	(560)

[a] The total dose may vary in the second decimal place due to rounding.

Table 5. The 30-, 50-, and 70-y integral effective dose for the various exposure pathways for the imported foods available diet.

	Effective integral equivalent dose, mSv		
Exposure pathway	30 y	50 y	70 y
Terrestrial food	82	110	130
External gamma	9.1	13	15
Marine food	0.048	0.096	0.16
Cistern and ground water	0.15	0.21	0.25
Inhalation	0.12	0.27	0.38
Total[a]	91	130	150

[a] The total dose may vary in the second decimal place due to rounding.

associated with the countermeasure option is listed in Table 9.

VALIDATION OF ENVIRONMENTALLY DERIVED DOSE ASSESSMENT

We assessed the "environmental data/model" approach by comparing our estimates of the body burden (i.e., dose) in people residing on Rongelap Atoll using our environmental data, the models and methods outlined in this paper, and three diet models with the actual whole-body measurements conducted by BNL.[†] The LLNL diet model predicts very closely the results of the whole-body measurements over an 8-y period. Two other proposed diet models lead to estimated body burdens far in excess of those observed by whole-body measurements. Results from Utirik Atoll are similar in that the LLNL diet model predicts actual observation while the other two proposed diets once again significantly exceed the observations. A more detailed analysis of this validation is given in a comparison paper in this issue (Robison and Sun 1997).

The estimated effective doses from plutonium based on the concentrations in food, soil and air are very similar to those calculated by BNL based on the analysis of plutonium in urine of the Rongelap people (Sun et al. 1992). These two very independent methods are in excellent agreement on the magnitude of the dose from the transuranic radionuclides as shown in Table 10. The estimated average committed effective dose for 50-y residence from plutonium based on environmental data and models is 0.26 mSv (0.10 mSv 50-y integral effective dose). The value of 0.40 mSv committed effective dose from urine analyses is based on the detection limit of the analytical method used for detection of plutonium in urine. The median value for plutonium in the urine of all the people analyzed is below this detection limit value. The people have been living on Rongelap Island for about 28 y subsequent to the fallout from BRAVO where the plutonium concentration in the surface soil is about 0.11 Bq g^{-1}. Consequently, both methods indicate that the effective committed dose from plutonium at Rongelap Island is below 0.40 mSv for residence between 30 and 50 y.

DISCUSSION

Comparison of estimated doses to adopted guidelines and to background doses

Perspective can be obtained by comparing these estimated doses for Bikini Island with natural background sources in the United States. The average annual effective dose from natural background sources in the United States is about 3 mSv y^{-1}; the breakdown by source is given in NCRP (1987a). The world-wide average background effective dose is 2.4 mSv y^{-1} with some areas over 10 mSv y^{-1} (UNSCEAR 1988). The maximum annual effective dose for current conditions on Bikini Island in 1999, using average values for parameters in the dose model, is 4.0 mSv y^{-1} when imported foods are available. This, of course, is above the average natural background doses in the U.S., but below that in some locations in the world (UNSCEAR 1988). The natural background dose in the Marshall Islands is about 2.4 mSv y^{-1} of which a significant fraction comes from

[†] Personal communications, Lessard, E. T.; Miltenberger, R., Brookhaven National Laboratory, Upton, NY; 1979.

Table 6. The maximum annual organ dose equivalent and effective dose rate in mSv y^{-1} for Bikini Island residents for the soil removal and potassium treatment option.

		Dose equivalent rate, mSv y^{-1}					
		Common to both diet 1 and 2		Diet 1[a] Imports available		Diet 2[b] Imports unavailable	
	Weight factor	External gamma	Internal inhalation	Internal ingestion	Total organ	Internal ingestion	Total organ
Bone marrow	0.12	0.16	0.0014	0.37	0.53	1.8	2.0
Bone surface	0.01	0.16	0.016	0.43	0.61	2.2	2.4
Gonads	0.20	0.16	0.00021	0.25	0.41	0.97	1.1
Lung	0.12	0.16	0.0023	0.22	0.38	0.87	1.0
Breast	0.05	0.16	4.3E-05	0.20	0.36	0.77	0.93
Thyroid	0.05	0.16	4.3E-05	0.23	0.39	0.89	1.1
Liver	0.05	0.16	0.0034	0.24	0.40	0.94	1.1
Colon	0.12	0.16	4.7E-05	0.27	0.43	1.2	1.4
Stomach	0.12	0.16	4.3E-05	0.23	0.39	0.92	1.1
Bladder	0.05	0.16	4.3E-05	0.24	0.40	0.97	1.1
Oesophagus	0.05	0.16	4.3E-05	0.23	0.39	0.89	1.1
Skin	0.01	0.16	4.3E-05	0.19	0.35	0.74	0.90
Remainder	0.05	0.16	4.3E-05	0.24	0.40	0.96	1.1
Total effective dose equivalent rate[c]					0.41		1.2

[a] Diet 1 = imported foods available diet (IA).
[b] Diet 2 = local foods only diet, i.e., imported foods unavailable (IUA).
[c] Weighting factor multiplied by total organ dose.

Table 7. The 30-, 50- and 70-y integral effective dose for Bikini Island residents for the soil removal/K treatment option when imported foods are available and when only local foods are consumed.

	Integral effective dose, mSv					
	30 y	30 y	50 y	50 y	70 y	70 y
External	3.6	(3.6)[a]	49	(49)	5.7	(5.7)
Internal						
Ingestion						
^{137}Cs	5.3	(21)	7.2	(28)	8.5	(33)
^{90}Sr	0.84	(5.9)	1.2	(8.6)	1.5	(10)
$^{239+240}Pu$	0.011	(0.098)	0.028	(0.24)	0.051	(0.44)
^{241}Am	0.011	(0.055)	0.026	(0.13)	0.045	(0.23)
Inhalation						
$^{239+240}Pu$	0.043	(0.043)	0.10	(0.10)	0.14	(0.14)
^{241}Am	0.04	(0.04)	0.08	(0.08)	0.11	(0.11)
Total[a]	9.8	(31)	14	(42)	16	(50)

[a] Numbers in parentheses are the doses for the "local food only" diet.
[b] The total dose may vary in the second decimal place due to rounding.

^{210}Po via consumption of fresh fish (Noshkin et al. 1994; Robison et al. 1997). Thus, the natural background dose plus the manmade component of the dose totals about 6.4 mSv, which is above the U.S. and world-wide average background dose, but still less than locations in some parts of the world (UNSCEAR 1988).

Guidance of 1 mSv y^{-1} for the general public from the International Commission and Radiological Protection (ICRP 1990) and the National Council on Radiation Protection (NCRP 1987b) are often quoted for reference. However, these guidelines are developed for controlling prospective dose; that is, for controlling future dose above a natural background baseline dose for practices such as nuclear power plants, uranium mining operations, fuel reprocessing plants, storage facilities, etc., that have a potential of exposing the general public. This

Table 8. The 30-, 50-, and 70-y integral effective dose for the soil removal/K treatment option for the various exposure pathways when imported foods are available.

	Effective integral equivalent dose, mSv		
Exposure pathway	30 y	50 y	70 y
Terrestrial food	6.0	8.3	9.8
External gamma	3.6	5	5.7
Marine food	0.048	0.096	0.16
Cistern and ground water	0.15	0.21	0.25
Inhalation	0.08	0.18	0.25
Total[a]	9.8	14	16

[a] The total dose may vary in the second decimal place due to rounding.

Table 9. Comparison of estimated effective doses for two diet models and two island conditions.

Diet model Island status	Imports available: Current conditions	Imports available: Soil + K treatment	Local foods only (imports unavailable): Current conditions	Local foods only (imports unavailable): Soil removal and K treatment
Maximum average annual effective dose, mSv	4.0	0.41	15	1.2
30 y integral dose, mSv	91	9.8	350	31
50 y integral dose, mSv	130	14	480	43
70 y integral dose, mSv	150	16	560	50

Table 10. The average committed effective dose from plutonium and americium at Rongelap Island in mSv.

	Method		
	Environmental (LLNL)[a]		Urine analysis (BNL)
	Committed effective dose	50-y integral effective dose	Committed effective dose
Plutonium	0.26	0.10	0.40[b]
Americium	0.23	0.078	No estimate

[a] Two significant figures to show slight difference between plutonium and americium.
[b] Based on the detection limit; actual dose is below this number.

guidance is not relevant to a situation such as in the Marshall Islands or other regions that have been contaminated where people wish to live.

For situations such as the Marshall Islands and areas contaminated by the Chernobyl accident, a new baseline of dose to the population has been created. The reduction of the new dose level by intervention strategies should be evaluated based on the reduced risk of detriment expected from the intervention relative to the dollar and social cost, environmental impact, and possible dose substitution resulting from the proposed remediation strategies. In other words, intervention should be considered only if it will do more good than harm.

Consequently, the decision to initiate intervention efforts will vary from case to case depending on the accompanying circumstances and issues. No specific guidance for an intervention level is given by any governing body, commission or board, but general guidance from the ICRP and IAEA can be used to infer an operational level. The ICRP (ICRP 1993b) has indicated that remedial actions, such as moving from one's house or paying for expensive remodeling, for people continually exposed in their homes to natural radon, is probably justified if the annual equilibrium radon concentration is above 600 Bq m^{-3} (an annual effective dose of about 10 mSv). This is based on intervention principles set forth in ICRP Publication 39 (ICRP 1984). This is a direct commentary on the difference in a policy or guidance designed for practices to limit the dose to the public where prospective dose can be controlled and limited in order to reduce even a small risk, and the case where previous contamination of a region is negatively affecting peoples lives. In the latter case, the guidance recognizes the fact that the risk is small from radiation doses that are above the prospective dose guidance but below about 10 mSv; such doses should not be used *a priori* as a basis for negatively affecting peoples lives, creating hardship, causing great expenditure of resources, or preventing people from occupying homes and lands. It is also a statement on the conservative nature of the prospective dose guidance.

The International Atomic Energy Agency (IAEA) in their Basic Safety Standards (BSS) (IAEA 1996) also indicate that the action level for remedial action for radon in dwellings should fall between 200 and 600 Bq m^{-3} yearly average concentration. Below this range remedial action would not be required. Moreover, the BSS state that lifetime doses, if projected to lead to a dose exceeding 1 Sv, should lead to permanent resettlement. With the radiological decay of ^{137}Cs over 70 y, this would translate into an initial dose rate below about 20 mSv y^{-1} for an action level. Some 51 countries and most organizations concerned with radiation protection were involved in the review and endorsement of the BSS.

The general consensus from major commissions and agencies is that below about 10 mSv y^{-1} the situation should be reviewed, and if a cost effective, socially-neutral impact, environmentally-sound remediation strategy can be found to reduce the dose further, then it should be considered. If not, resettlement of homes and lands should not necessarily be prohibited.

The application of potassium to the surface soil and the subsequent dissolution and transport into the root zone during periods of rainfall is very effective in reducing the concentration of ^{137}Cs in edible foods. If a reasonable agricultural program is implemented that includes periodic use of fertilizer, the dose from ^{137}Cs through the food chain will be greatly reduced, and the growth and productivity of some plants and food crops will be enhanced. The variety of food crops at Bikini Island that have been treated with potassium in our field experiments have shown a reduction in the concentration of ^{137}Cs to about 5% of pretreatment concentrations. The resulting ^{137}Cs concentration in food crops is between 100 and 200 Bq kg^{-1}.

The Codex Alimentarius Commission has established guidelines for the concentration of various radionuclides in foodstuffs that may be shipped across international borders (FAO/WHO 1991). The concentrations below which foods can be transported across international boundaries and used for general food consumption are listed in Table 11. The concentration for ^{137}Cs in foods is 1,000 Bq kg^{-1}. The ^{137}Cs concentration in food products at Bikini fall between 100–200 Bq kg^{-1} after potassium treatment, which is well below the Codex Alimentarius guidelines.

This use of potassium fertilizer, coupled with the soil removal and addition of crushed coral in the housing and village areas, could reduce the average maximum annual dose from about 4.0 mSv to about 0.41 mSv. Consequently, the combined natural background and manmade dose after potassium treatment is 2.8 mSv y^{-1} (2.4 mSv y^{-1} + 0.41 mSv y^{-1}), which is similar to the U.S. average annual background dose of 3 mSv. The average background dose in the U.S. over a 50-y period is 150 mSv. The average background dose in the Marshall Islands over 50 y is estimated to be 120 mSv (Robison et al. 1997); the 50-y integral effective dose at Bikini Island after the soil removal/potassium treatment remedial action is estimated to be 14 mSv. Consequently, the combined dose at Bikini, natural background plus manmade, for a 50-y period is about 134 mSv, after the remedial action. Thus, because of the radiological decay of ^{137}Cs, the combined natural background dose and the dose from the manmade component (^{137}Cs, ^{90}Sr, $^{239+240}Pu$, ^{241}Am) over 50 y is about the same as the 50-y natural background dose in the U.S. and the world-wide average. The ^{137}Cs, ^{90}Sr, $^{239+240}Pu$ and ^{241}Am are still in the soil although the ^{137}Cs uptake into foods is greatly reduced. However, the half-life of ^{137}Cs is 30.1 y (and 28 y for ^{90}Sr) so that in 120 y the ^{137}Cs will be about 6% of the current concentrations. That will in effect bring the ^{137}Cs concentration to levels that don't require a remedial action. This is less time than it will take to rebuild the soil if the top 40 cm of the island is excavated and discarded.

Moreover, we continually see ^{137}Cs in the groundwater at all contaminated atolls; the turnover time of the groundwater is about 5 y. The ^{137}Cs can only get to the groundwater by a leaching process through the soil column when a portion of the soluble fraction of ^{137}Cs is transported to the groundwater when rainfall is heavy enough to cause recharge of the lens. Environmental processes are causing a loss of ^{137}Cs out of the root zone of the plants that provides a loss constant (λ env) in addition to radiological decay. Consequently, there is an effective rate of loss, λ eff = λ rad + λ env that is the sum of the radiological and environmental-loss decay constants. We have had, and continue to have, a vigorous program to determine the rate of the environmental loss process. What we do know at this time is that the loss of ^{137}Cs over time is greater than that estimated based on only radiological decay.

Table 11. Generic action levels for foodstuffs.

Radionuclides	Foods destined for general consumption (kBq kg^{-1})	Milk, infant foods and drinking water (kBq kg^{-1})
^{134}Cs, ^{137}Cs, ^{103}Ru ^{106}Ru, ^{89}Sr	1	1
^{131}I		0.1
^{90}Sr	0.1	
^{241}Am, ^{238}Pu, ^{239}Pu	0.01	0.001

CONCLUSIONS

The dose to populations resettling contaminated atolls in the Northern Marshall Islands is dominated by ^{137}Cs that is transported from soil to the edible portions of plants. The dose from ^{137}Cs uptake via the terrestrial food chain accounts for about 90% of the estimated dose at Bikini Island. ^{90}Sr contributes a very small percentage of the estimated dose because of the unique Ca CO_3 soil system. In fact, the relative uptake of ^{137}Cs and ^{90}Sr in food crops at the atolls is totally reversed from that observed in continental, silica-based soils. Most all the data in the literature are based on experiments and observations from silica-based soils. The transuranic radionuclides, $^{239+240}Pu$ and ^{241}Am, contribute in a minor way to the estimated dose, but they will, of course, have a long-term presence at the atolls. External gamma is the second most significant pathway because of the dose resulting from ^{137}Cs (Ba) gamma rays. The inhalation, drinking water, and marine food pathways contribute only slightly to the estimated dose at the atolls.

The estimated dose to the returning populations under current island conditions will exceed background doses elsewhere in the world. However, two different remedial actions, excavation of the top soil and treatment with potassium fertilizer, will reduce the dose at Bikini Atoll so that the combined natural background dose plus the dose from manmade radionuclides of bomb origins will be less than natural background dose in the continental United States and Europe. Both remedial methods will reduce the concentration of ^{137}Cs in food crops to levels well below the Codex Alimentarius guidelines of 1000 Bq kg^{-1} (Codex 1994). Foods with a concentration of ^{137}Cs below 1,000 Bq kg^{-1} are allowed to be shipped across international borders for general use in the food supply.

Based upon the extensive data base of radionuclide concentrations in the Bikini Island environment, the dose assessments based on detailed evaluation of all exposure pathways, and field experiments to evaluate remedial options, several measures are identified to reduce the dose to returning populations along with commentary on their effectiveness and the positive and negative aspects of each:

1. Remove the surface soil (0 to 30 cm) in the area where the village will be established and for 10 to 15 m around each of the sites where houses will be built to minimize the external gamma and beta and alpha

exposure in the areas where people spend most of their time. The estimated gamma dose can be reduced by 40% by such action. The additional cost to remove 15 to 20 cm of soil from the relatively small area included around each house and the village area would be minimal, compared with the overall costs of resettlement, since scraping and clearing is required to begin construction and resettlement. There would essentially be no adverse environmental effects from such an action.

2. Place a 10-cm layer of crushed coral around the village site and in a 5 to 10-m radius around each house to provide some additional reduction in any beta and gamma rays emanating from the soil subsequent to the soil removal and greatly reduce exposure to any residual beta radiation. This should be acceptable, as it is common practice in Marshallese villages to use crushed coral around homes for both appearance and dust suppression. The combination of the soil removal and application of crushed coral can significantly reduce the external exposure and provide small reductions in internal exposure.
3. Treat the entire agricultural area of the island, where coconut, breadfruit, and *Pandanus* fruit are growing, with potassium chloride (KCl) or complete fertilizer (nitrogen, phosphorus, and potassium) to reduce the uptake of ^{137}Cs into food crops. A high-potassium fertilizer can also be used in any family-type gardening for the same reason. This option reduces the estimated dose to 5% of pretreatment estimates and minimizes the environmental impact. The major portion of the island will be left intact including the mature coconut grove, the surface soil that contains nearly all of the organic material of the soil that has taken centuries to develop, and the natural vegetation windbreaks along the shoreline. The organic soil layer is very important for growing natural vegetation and food crops; it provides most all of the nutrients required for plant growth, and increases the water retention capacity of the soils. The potential reduction in estimated dose from the food chain can be 95%. This plan, coupled with the soil removal and addition of crushed coral in the housing and village areas would have two positive effects. First, it could reduce the maximum annual dose (assuming a mixed diet of local and imported foods) from 4.0 mSv to about 0.41 mSv and the total estimated 30-y, integral effective dose at Bikini Island from 91 mSv to about 9.8 mSv. Second, it would be helpful to crop production by increasing the growth rate and productivity of some food crops. The ^{137}Cs, ^{90}Sr, $^{239+240}Pu$, and ^{241}Am are still in the soil although the ^{137}Cs uptake into foods is greatly reduced. Thus, the potassium treatment can solve the major dose problem until natural radionuclide decay reduces the ^{137}Cs to insignificant levels in about 90 y. The dose from ^{90}Sr is very low because of all the excess calcium and stable strontium in the calcareous, coralline soils that greatly reduces the uptake of ^{90}Sr in food crops. The ^{90}Sr has a slightly shorter half life than ^{137}Cs and will also be reduced to insignificant levels within about 100 y.
4. Design adequate water catchment systems so that fresh water will always be available, even during extended dry periods, thus avoiding use of the contaminated ground water. Although the reduction in the estimated dose from the ground-water pathway (it contributes less than 0.05% of the estimated dose) is very much less than for the external gamma and terrestrial food pathways, it is not an expensive proposition to expand somewhat the water catchment systems that will be a necessary part of any housing and community design. Again, apart from radiological considerations, this measure should be found acceptable because of the obvious community benefits of expanded and improved water catchment systems. Consequently, another potential source of exposure, albeit very low, can essentially be eliminated.
5. Of course, excavation of the top 30 to 40 cm of soil over the whole island also will effectively reduce the potential dose, both external and internal. This option, however, would entail environmental cost, as well as high dollar cost. The removal of the top 30 to 40 cm of soil would carry with it the removal of essentially all of the organic material—material that has taken centuries to develop and that contains most all of the nutrients required for plant growth and that increases water-retention capacity of the coral soil. This would obviously require removing all the mature coconut trees and other trees that supply food, windbreak, and shade at the island. This option would thus necessitate a very long-term commitment to rebuild the soil and revegetate the island. Such a commitment would, in turn, seem to suggest a continuous infusion of effort and expertise, the availability of which does not now seem assured.

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